NASA Technical Paper 1688

Cold-Air Investigation of a 4 1/2-Stage Turbine With Stage-Loading Factor of 4.66 and High Specific Work Output

II - Stage Group Performance

Warren J. Whitney, Frank P. Behning,
Thomas P. Moffitt, and Glen M. Hotz

JUNE 1980

NASA

NASA Technical Paper 1688

Cold-Air Investigation of a 4 1/2-Stage Turbine With Stage-Loading Factor of 4.66 and High Specific Work Output

II - Stage Group Performance

Warren J. Whitney, Frank P. Behning,
Thomas P. Moffitt, and Glen M. Hotz
Lewis Research Center
Cleveland, Ohio

National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1980

A

Summary

The stage group performance of a 4½-stage turbine with an average stage-loading factor of 4.66 and high specific work output was determined in cold air at design equivalent speed. The 4-stage turbine configuration produced design equivalent work output with an efficiency of 0.856; a barely discernible difference from the 0.855 obtained for the complete 4½-stage turbine in a previous investigation. The effect of the outlet-turning-vane pressure loss on efficiency for this turbine was estimated to be 0.005. The contractor's efficiency forecast for the 4½-stage turbine was 0.886, and the value predicted by Lewis using a reference method was 0.862. The efficiencies of the stage groups at their respective design work outputs varied from 0.007 low for the 4½-stage turbine to 0.021 low for the single-stage configuration—as compared with predicted efficiency. The individual stage efficiencies were compared with the predicted efficiency for the condition at which design 4½-stage work output was obtained. The efficiencies of stages 1 and 4 were about 0.020 lower than the predicted value, that of stage 2 was 0.014 lower, and that of stage 3 was about equal to the predicted value. Thus all the stages operated reasonably close to their expected performance levels, and the overall (4½-stage) performance was not degraded by a particularly inefficient component.

Introduction

In recent years the NASA Lewis Research Center has been concerned with turbines designed with a high stage-loading factor (e.g., refs. 1 to 4). The high stage-loading factor (ratio of change in tangential velocity to blade speed) occurs for direct-drive fan turbines that are limited by fan tip speed, especially for high-bypass-ratio engines. This type of turbine is characterized by large turning angles, low blade speed, nearly symmetrical mean-radius velocity diagrams, and shrouded rotor blades. The alternative to using a turbine design with a high stage-loading factor (3 to 5) is to use conventional loading factors (1.5 to 2) and thereby to double or triple the number of turbine stages.

The subject turbine evolved from a study that Pratt & Whitney Aircraft of East Hartford, Connecticut, made of the engine requirements for an advanced transport airplane. The turbine was designed and fabricated by Pratt & Whitney under a cost-sharing contract with Lewis. The turbine was a one-half scale model of the actual engine turbine. The turbine consisted of four stages with outlet turning vanes and had an average stage-loading factor of 4.66. The turbine design procedure is described in reference 4, wherein the contractor's anticipated efficiency was given as 0.886 for the complete turbine and 0.893 for the four-stage configuration. The salient features of the design procedure were controlled vortex flow, tailored radial work distribution, and control of the location of boundary-layer transition point on the airfoil suction surface. The contractor contended that incorporating these design features would improve performance. Lewis forecast an efficiency of 0.862 for this turbine by using the efficiency trends of reference 5 and the outlet-turning-vane loss estimate of reference 6.

The overall performance of the 4½-stage turbine was determined at Lewis in a cold-air investigation (ref. 7); the efficiency at design specific work output was 0.855. This efficiency was 0.007 lower than the Lewis prediction and was comparable to that of contemporary high-stage-loading-factor turbines designed with free-vortex flow. Thus the turbine did not demonstrate the performance improvement anticipated by the contractor.

In an attempt to understand better the factors contributing to this overall performance, experimental performance was obtained for the different stage groups. These groups consisted of stages 1 to 4, stages 1 to 3, stages 1 and 2, and stage 1. Appropriate outlet fairing pieces were designed and fabricated to provide an adequate outlet measuring station for each stage group. The performances of the stage groups were obtained at equivalent design speed over a range of total-pressure ratio. All tests were conducted at an inlet pressure of 2.4 atmospheres. The single-stage configuration was tested with the inlet temperature maintained at 378 K (680° R), and all other stage groups were tested at an inlet temperature of 444 K (800° R). The results of the stage group investigations are presented herein. The efficiencies of the stage groups are compared with their estimated efficiencies at their respective design specific work outputs. In addition, the efficiencies of the individual stages are derived from the stage group results for the condition where design work output was obtained for the 4½-stage turbine.

Symbols

A	area, m^2 (ft^2)
$\overline{D}_m$	effective mean blade diameter, $\left(\frac{D^2_{m,1}+D^2_{m,2}+D^2_{m,3}+D^2_{m,4}}{4}\right)^{1/2}$, m (ft)
$D_{m,1}, D_{m,2}, D_{m,3}, D_{m,4}$	mean diameters of first, second, third, and fourth stages, respectively
g	force-mass conversion constant, 1 (32.174 ft/sec^2)
h	specific enthalpy, J/g (Btu/lb)
N	rotative speed, rpm
n	number of stages
P	absolute pressure, N/m^2 (lb/ft^2)
R	gas constant for mixture of air and combustion products used in this investigation, 287.9 J/kg K (53.463 ft-lb/lb °R) for $T_0' = 444$ K (800° R); 288.0 J/kg K (53.527 ft-lb/lb °R) for $T_0' = 378$ K (680°R)
T	temperature, K (°R)
$\overline{U}_m$	effective mean blade speed, $\pi \overline{D}_m N/60$, m/sec (ft/sec)
w	mass flow rate (sum of air and fuel), kg/sec (lb/sec)
$\overline{\alpha}$	average absolute gas flow angle at turbine outlet measured from axial direction irrespective of sign, used in eq. (2), deg
γ	ratio of specific heats, for mixture of air and combustion products used in this investigation, 1.3949 at $T_0' =$ 444 K (800° R); 1.3980 at $T_0' =$ 378 K (680° R)
δ	ratio of inlet pressure to U.S. standard sea-level pressure
ϵ	function of γ, $(0.73959/\gamma)[(\gamma+1)/2]^{\gamma/(\gamma-1)}$
η	efficiency based on total-pressure ratio
θ_{cr}	squared ratio of critical velocity at turbine inlet to critical velocity of U.S. standard sea-level air
τ	torque, N-m (ft-lb)
Subscripts:	
cr	condition at Mach 1
x	outlet station for a blade group (fig. 3)
0	station at turbine inlet (fig. 3)
0.5,1.0,1.5, 2.0,2.5,3.0, 3.5,4.0	interstage cavity pressure-tap stations (fig. 3)
4.5	station at turbine outlet (fig. 3)
Superscript:	
′	total state

Turbine

The turbine, as mentioned in the Introduction, was a one-half scale model of the fan-drive turbine that evolved from a study of the engine for an advanced transport airplane. The pertinent features and requirements of the model turbine are as follows:

Number of stages, n	4
Average stage-loading factor, $\Delta h \times 10^3/(n \times \overline{U}^2_m)$	4.66
Equivalent specific work, $\Delta h/\theta_{cr}$, J/g (Btu/lb)	104.44(44.9)
Equivalent mass flow, $\epsilon w\sqrt{\theta_{cr}}/\delta$, kg/sec (lb/sec)	6.078(13.4)
Equivalent effective mean blade speed, $\overline{U}_m$, m/sec (ft/sec)	74.905(245.75)
Effective mean diameter, $\overline{D}_m$, m (ft)	0.48006(1.575)
Equivalent rotative speed, $N/\sqrt{\theta_{cr}}$, rpm	2980
Total-pressure ratio, $P_0'/P_{4.5}'$, based on estimated efficiency of 0.886	6.18
Inlet conditions for design Reynolds number:	
Total pressure, P_0', atm	1.565
Total temperature, T_0', K (°R)	422(760)

The contractor's design philosophy and procedure are discussed in reference 4. The design velocity diagrams are shown in references 4 and 7 and are included in this report in figure 1. As mentioned in reference 4 the design work split among the four stages was nearly equal, being 25.5, 25.9, 24.5, and 24.1 percent for stages 1 to 4, respectively. The use of outlet turning vanes permits loading the last stage to about the same degree as the other stages because the vanes convert the whirl energy out of the last stage into dynamic head that is useful for propulsive thrust. The velocity diagram was a forced-vortex type. The axial velocity for this type of diagram decreases from mean to tip section and increases from mean to hub section. The specific work output was varied radially to reduce the work near the hub and tip endwalls for all four stages.

The blading passages and profiles are shown in figure 2, the flowpaths for the different stage groups in figure 3, the instrumentation plans for the different configurations in figure 4, and the turbine rotor assembly in figure 5.

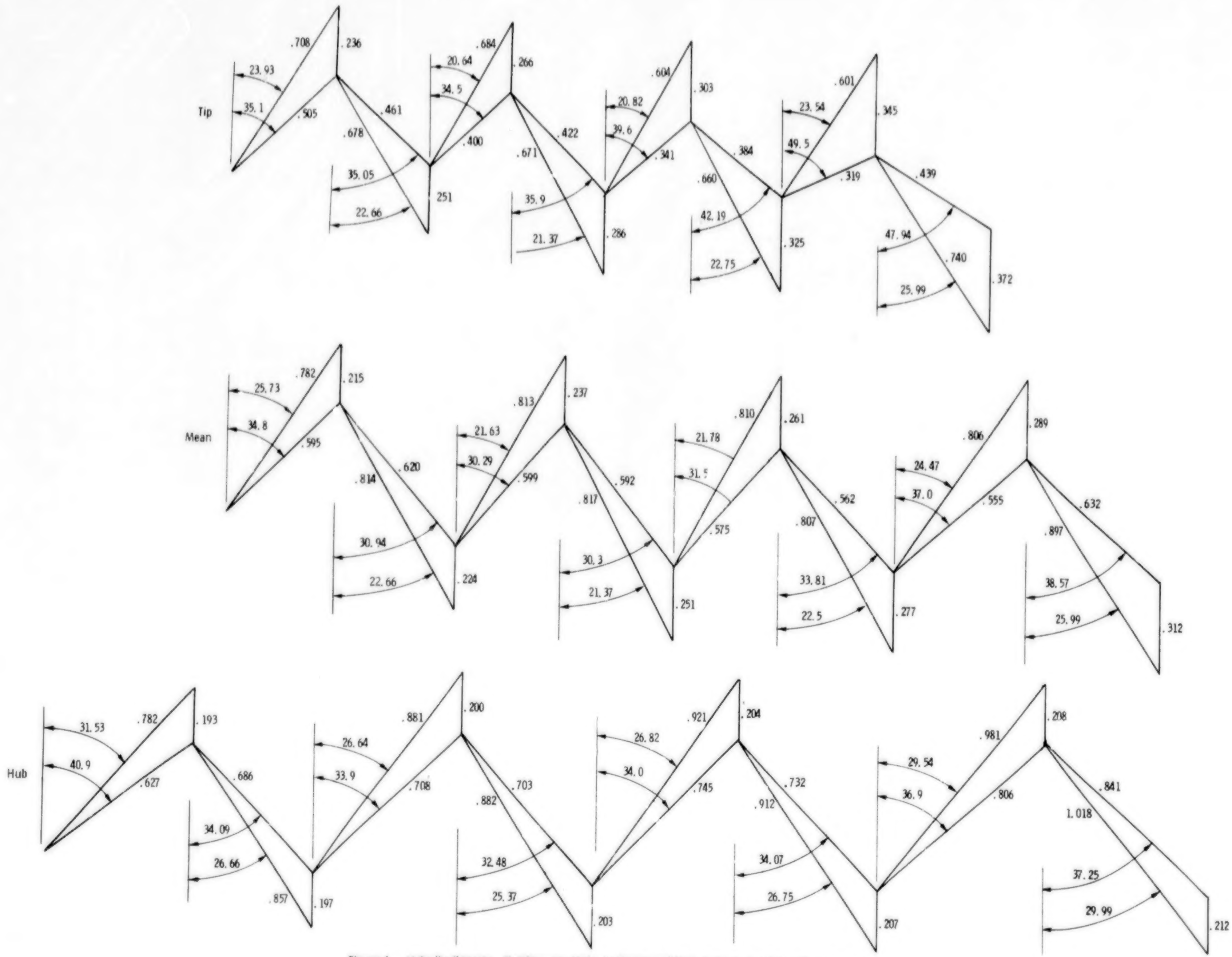


Figure 1. - Velocity diagrams. Numbers are angles in degrees and Mach numbers at airfoil exit. (From ref. 4.)

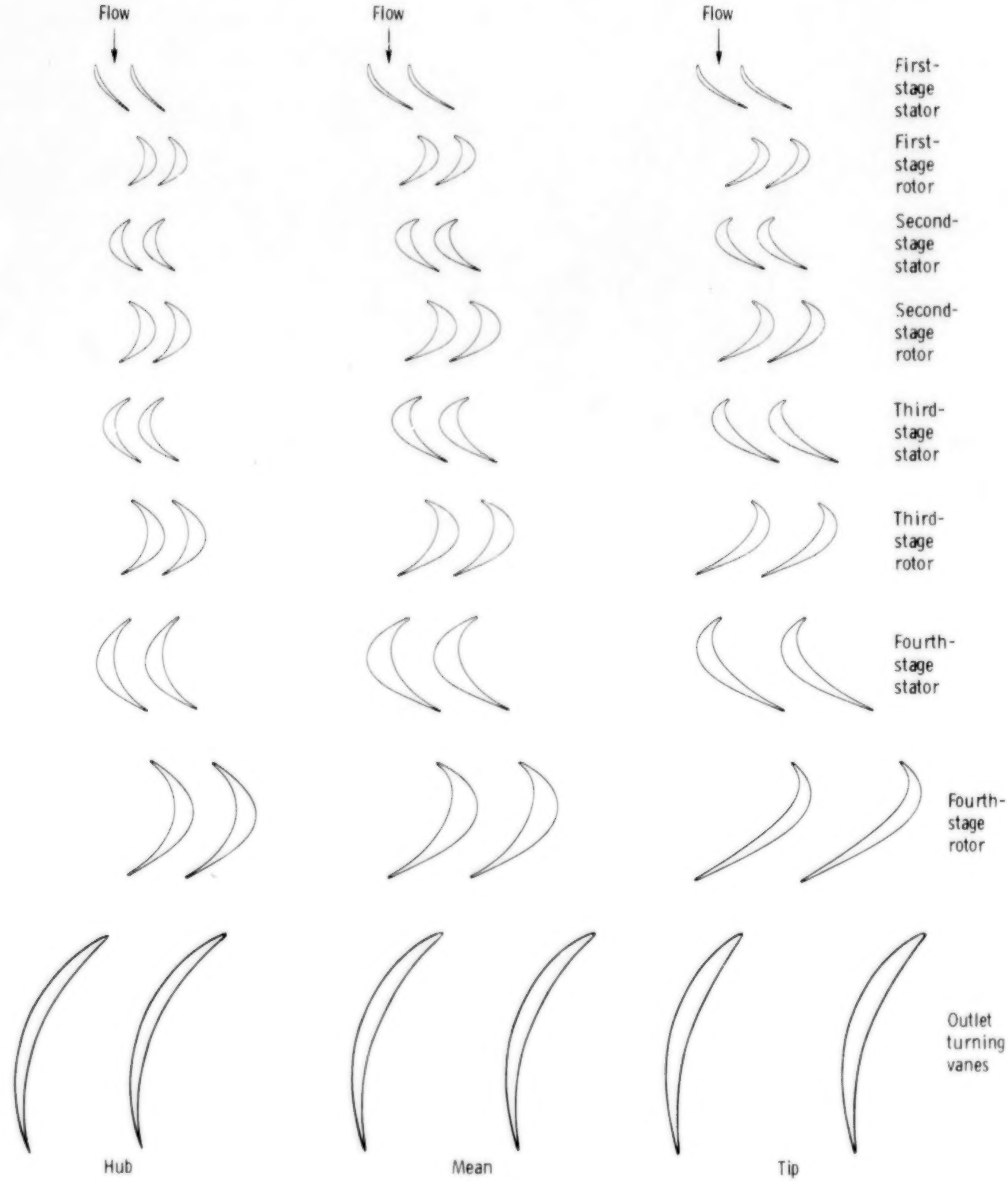
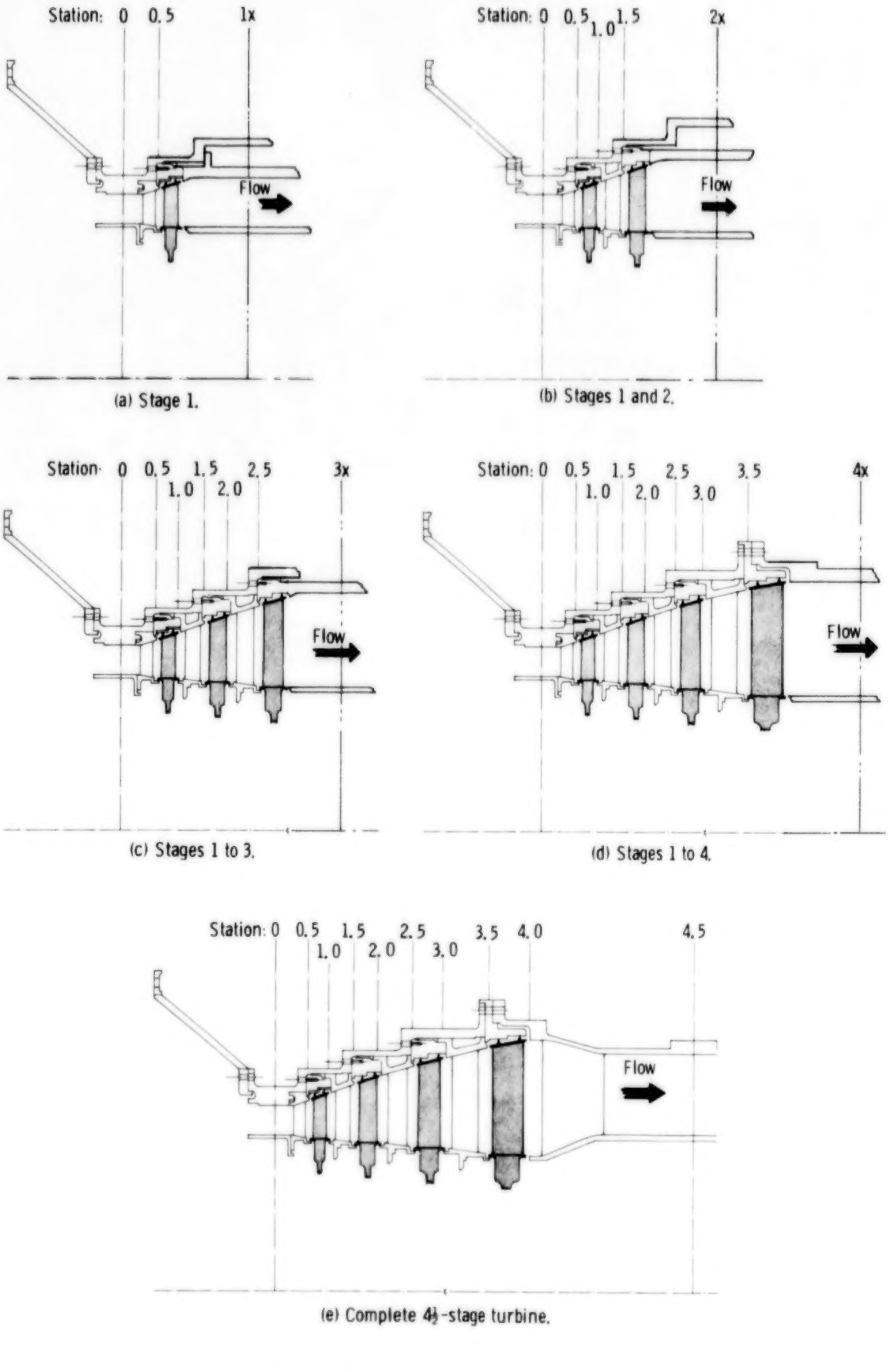


Figure 2. - Turbine blading passages and profiles.



(a) Stage 1.

(b) Stages 1 and 2.

(c) Stages 1 to 3.

(d) Stages 1 to 4.

(e) Complete $4\frac{1}{2}$-stage turbine.

Figure 3. - Flowpath and instrumentation stations.

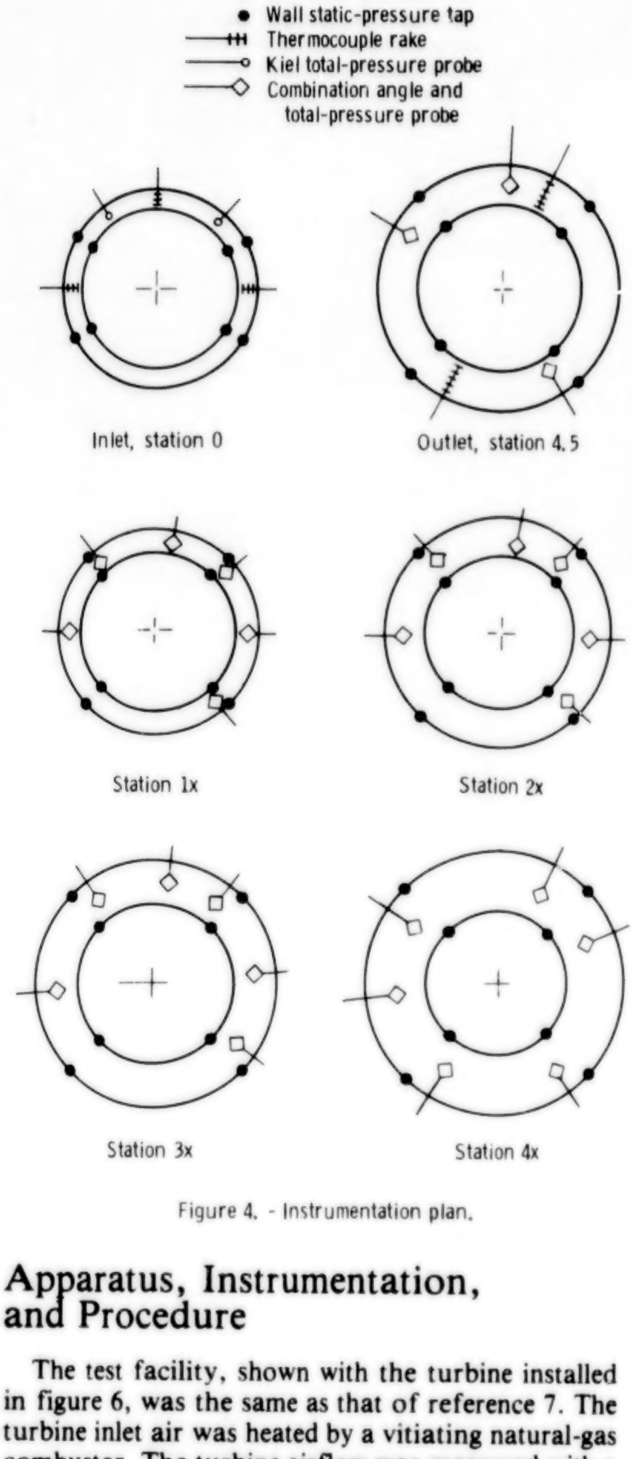


Figure 4. - Instrumentation plan.

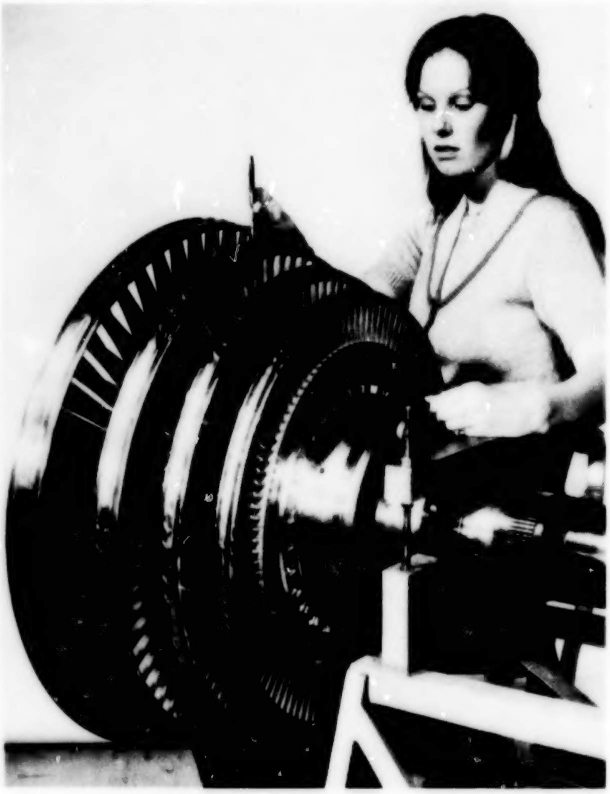


Figure 5. - Turbine rotor assembly.

Apparatus, Instrumentation, and Procedure

The test facility, shown with the turbine installed in figure 6, was the same as that of reference 7. The turbine inlet air was heated by a vitiating natural-gas combustor. The turbine airflow was measured with a Dall tube, which is a modified form of venturi meter. The fuel flow was metered with a flat-plate orifice. Both flow-rate measurements required an upstream pressure measurement, an upstream temperature measurement, and a differential pressure measurement across the flowmeter element. The turbine mass flow was obtained as the sum of the fuel and air flows.

The turbine shaft speed was measured with a magnetic pickup and a square tooth sprocket that was mounted on the turbine shaft. The electrical impulses were converted to shaft rotative speed with an electronic counter. Turbine torque was measured as the reaction torque on the dynamometer stator with a strain-gage load cell. The dynamometer stator was cradled and supported by a high-pressure oil film (hydrostatic trunnion bearing).

The turbine test section was instrumented as shown in figures 3 and 4. Station 0 was common to all stage groups. For all the configurations except the complete 4½-stage turbine, it was necessary to design and fabricate fairing pieces in which to locate the measuring stations 1x, 2x, 3x, and 4x. These fairings were required to provide a well-machined cylindrical surface for an adequate distance upstream and downstream of the measuring station. The interstage taps at stations 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 were installed (three at each station) in the outer clearance space. It was intended to use these reference pressure ratios (cavity to inlet total) to isolate the performance of the individual stages.

The total temperature at the turbine inlet was measured with nine thermocouples—three rakes of three each. These temperatures were corrected for recovery coefficient and then averaged to obtain the

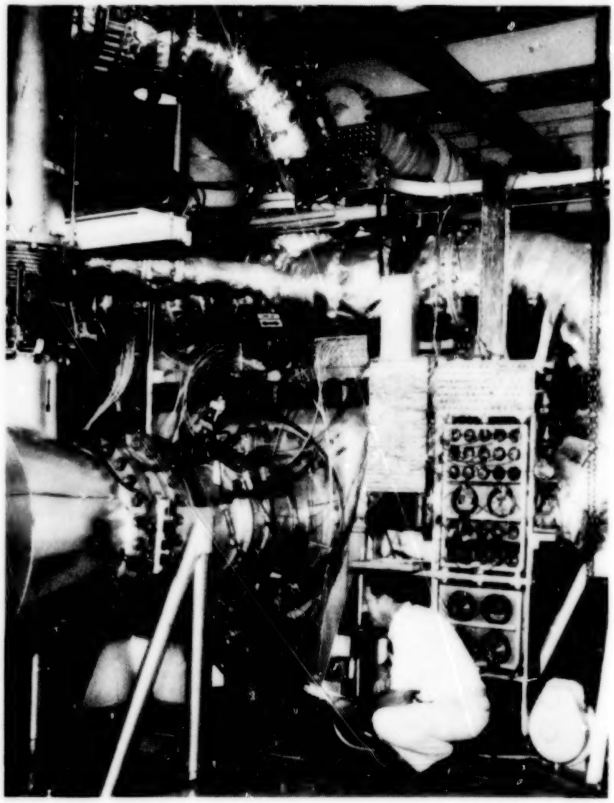


Figure 6. - Turbine installed in test facility.

inlet total temperature T_0. The static pressure P_0 was obtained by averaging the readings from the eight wall static-pressure taps. The total pressure was then calculated from the following equation:

$$\frac{P_0'}{P_0} = \left\{ \frac{1}{2} + \left[\frac{1}{4} + \frac{\gamma - 1}{2g\gamma} \left(\frac{w}{P_0 A_0} \right)^2 R T_0' \right]^{1/2} \right\}^{\gamma/(\gamma-1)} \quad (1)$$

as in reference 7.

At the turbine outlet (stations 1x, 2x, 3x, or 4x) the static pressure was also obtained by averaging the readings from the eight wall static-pressure taps. The total temperature was determined from the inlet total temperature and the specific enthalpy drop, which in turn was determined from the torque, speed, and mass flow measurements. The equation for outlet total pressure (for the 4-stage configuration) was

$$\frac{P_{4x}'}{P_{4x}} = \left\{ \frac{1}{2} + \left[\frac{1}{4} + \frac{\gamma - 1}{2\gamma g} \left(\frac{w}{P_{4x} A_{4x}} \right)^2 \frac{R T_{4x}'}{\cos^2 \bar{\alpha}_{4x}} \right]^{1/2} \right\}^{\gamma/(\gamma-1)} \quad (2)$$

The angle $\bar{\alpha}_{4x}$ is the average deviation from the axial direction irrespective of sign.

All the data were obtained at design speed over a range of pressure ratio bracketing design specific work output. The inlet total temperature was 378 K (680° R) for the first stage operated as a single-stage turbine. The inlet temperature was maintained at 444 K (800° R) for the other configurations. The inlet total pressure for all tests was 2.4 atmospheres.

Results and Discussion

This section describes the performances of the stage groups and compares them to predicted stage group performance. In addition, the performances of the individual stages are derived for the condition at which the design 4½-stage specific work output was obtained.

Four-Stage Turbine

The experimental results for the 4-stage configuration are displayed in figure 7 as equivalent torque, equivalent mass flow, equivalent specific work output, efficiency, and exit flow angle—all shown as functions of total-pressure ratio. The corresponding results from the 4½-stage turbine (ref. 7) are included for comparison. The outlet turning vanes had a very slight effect on the performance parameters in figures 7(a) to (d). The efficiency at design specific work output, 104.44 joules per gram (44.9 Btu/lb), was 0.856 for the 4-stage turbine and 0.855 for the 4½-stage turbine (fig. 7(d)). The predicted efficiency difference for these two turbines was 0.005, based on the outlet-turning-vane total-pressure loss estimated from reference 6. As would be expected, the exit flow angles of the two turbines differed considerably (fig. 7(e)). The angle was nearly axial (within 6°) for the 4½-stage turbine over the range of pressure ratio because of the outlet turning vanes. The exit flow angle of the 4-stage turbine varied with pressure ratio and was 52.6 at design specific work output. The average exit angle determined from the velocity diagram was 50.6°. Both turbine configurations were choked at a pressure ratio well below that corresponding to design specific work output. Their choking mass flow was 6.033 kilograms per second (13.30 lb/sec); the design mass flow was 6.078 kilograms per second (13.40 lb/sec).

Three-Stage Turbine

The performance of the stage group consisting of the first, second, and third stages is shown in figure 8. The choking equivalent mass flow was 6.028 kilograms per second (13.29 lb/sec) (fig. 8(b)). Although this value should be at least equal to the 6.033 kilograms per second (13.30 lb/sec) obtained for the 4-stage turbine, the choking mass flows for

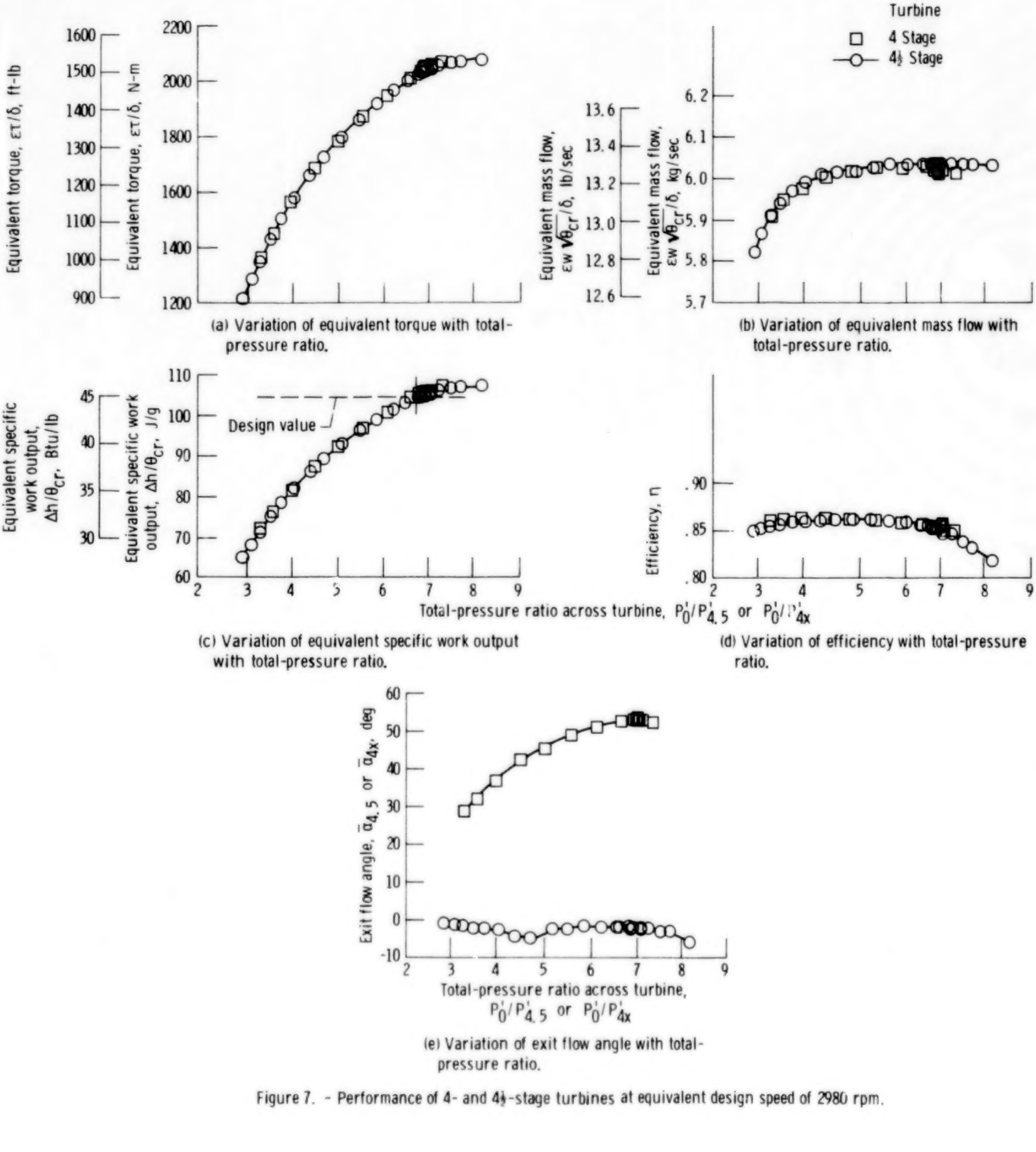
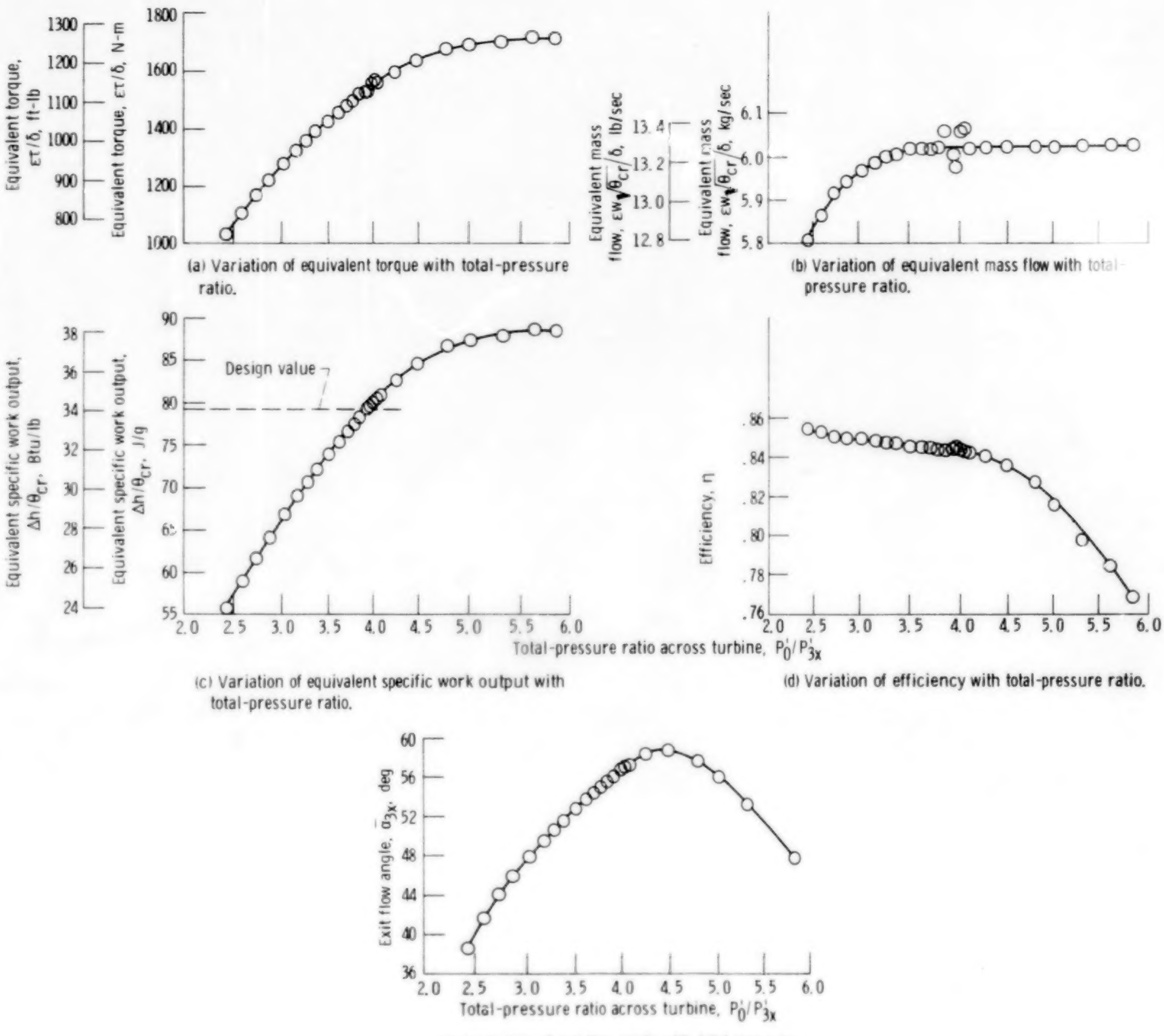


Figure 7. - Performance of 4- and 4½-stage turbines at equivalent design speed of 2980 rpm.



(a) Variation of equivalent torque with total-pressure ratio.

(b) Variation of equivalent mass flow with total-pressure ratio.

(c) Variation of equivalent specific work output with total-pressure ratio.

(d) Variation of efficiency with total-pressure ratio.

(e) Variation of exit flow angle with total-pressure ratio.

Figure 8. - Performance of 3-stage turbine at equivalent design speed of 2980 rpm.

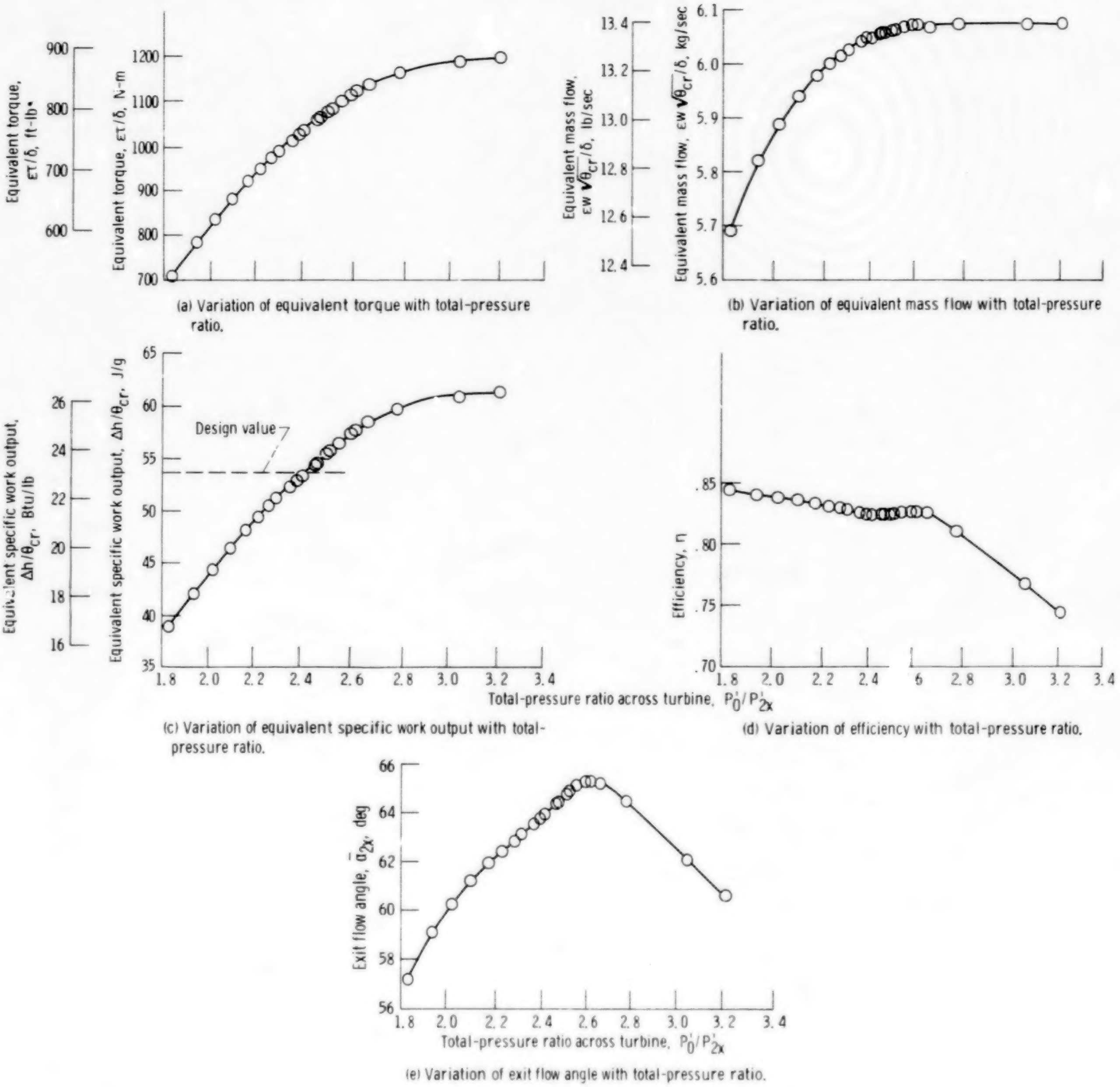
the two configurations do agree to within 0.1 percent. The 3-stage turbine developed design specific work output, 79.22 joules per gram (34.06 Btu/lb), at a total pressure ratio P_0'/P_{3x}' of 3.913 (fig. 8(c)). The efficiency at this pressure ratio was 0.844 (fig. 8(d)), and the average exit flow angle was 55.9° (fig. 8(e)). The average exit angle out of the third stage as determined from the design velocity diagram was 55.2°.

Two-Stage Turbine

The performance of the 2-stage configuration, consisting of the first and second stages, is shown in figure 9. The correlation of equivalent torque with pressure ratio was very good (fig. 9(a)). The equivalent mass flow curve (fig. 9(b)) shows that the 2-stage turbine choked at a flow rate of 6.074 kilograms per second (13.39 lb/sec), or 1.007 that of the 4-stage turbine. The 2-stage turbine developed design specific work output, 53.61 joules per gram (23.05 Btu/lb), at a pressure ratio of 2.422 (fig. 9(c)). The efficiency at this condition was 0.825 (fig. 9(d)). The average outlet angle at design work output was 64° (fig. 9(e)); the average second-stage exit flow angle based on the design velocity diagram was 58.6°.

Single-Stage Turbine

The performance results of the first stage operated as a single-stage turbine are shown in figure 10. Excellent correlation was obtained when equivalent



(a) Variation of equivalent torque with total-pressure ratio.

(b) Variation of equivalent mass flow with total-pressure ratio.

(c) Variation of equivalent specific work output with total-pressure ratio.

(d) Variation of efficiency with total-pressure ratio.

(e) Variation of exit flow angle with total-pressure ratio.

Figure 9. - Performance of 2-stage turbine at equivalent design speed of 2980 rpm.

torque $\epsilon\tau/\delta$ was plotted as a function of pressure ratio P_0'/P_{1x}' (fig. 10(a)). The choking mass flow (fig. 10(b)) for the single-stage turbine was 6.228 kilograms per second (13.73 lb/sec), which was 1.025 the design mass flow or 1.032 the 4-stage choking mass flow. The single-stage turbine produced design work output, 26.61 joules per gram (11.44 Btu/lb), at a pressure ratio P_0'/P_{1x}' of 1.505 (fig. 10(c)). The efficiency at this pressure ratio was 0.835 (fig. 10(d)). The turbine outlet flow angle at design work output was 62.1° (fig. 10(e)); the average angle from the velocity diagram was 58.1°.

Comparison of Stage Groupings

The stage group performances are compared in table 1, with each group at its respective design work output. The stage group efficiencies were generally 1 to 2 points lower than the predicted efficiency. The overall (4½ stage) efficiency was 0.007 lower than the predicted efficiency and 0.031 lower than the manufacturer's estimated efficiency (as noted in ref. 7).

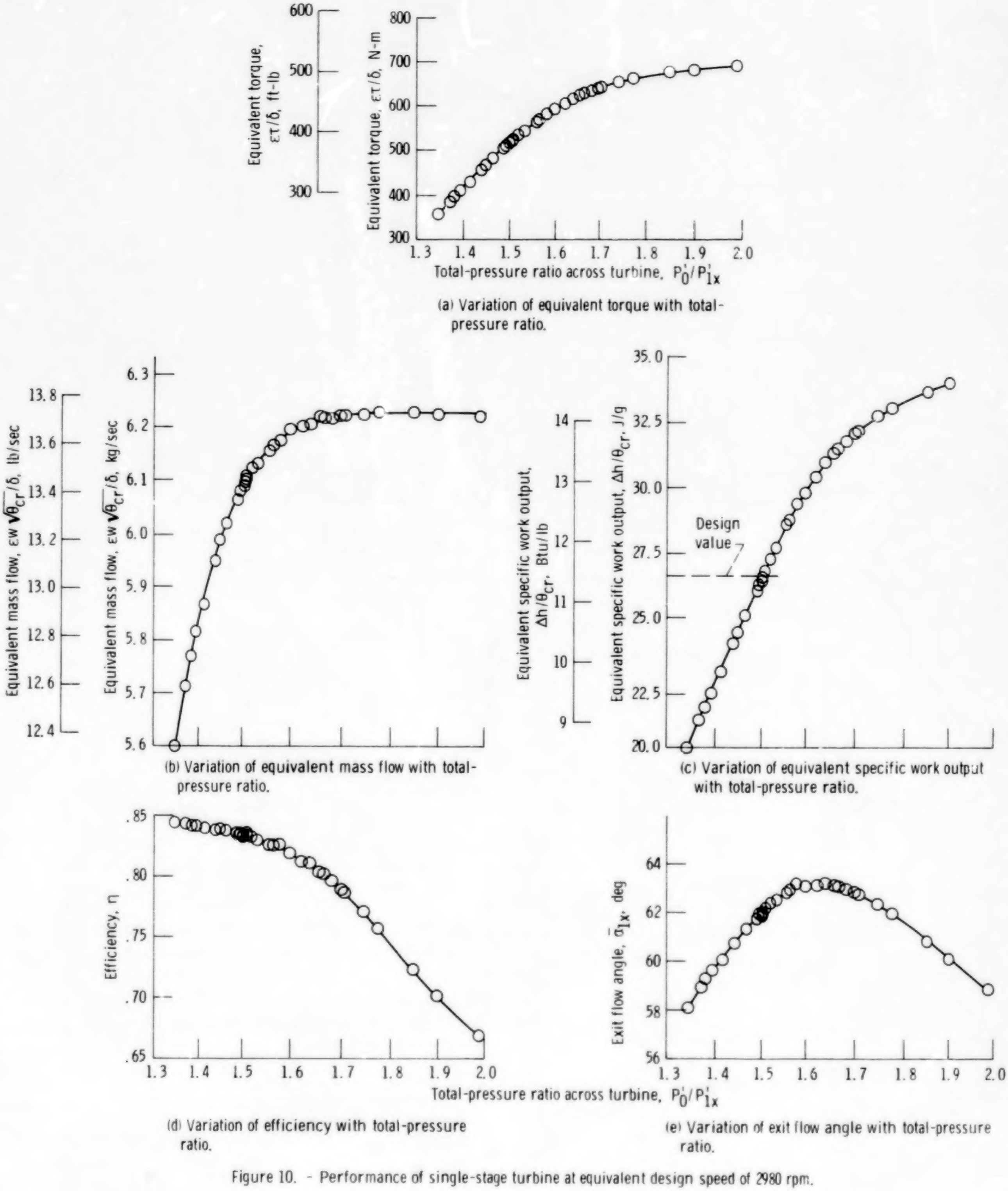


Figure 10. - Performance of single-stage turbine at equivalent design speed of 2980 rpm.

TABLE II. - COMPARISON OF INDIVIDUAL STAGE

PERFORMANCE AT CONDITION AT WHICH DESIGN

$4\frac{1}{2}$-STAGE WORK OUTPUT WAS OBTAINED

Stage	Experimental work output		Design work output		Experimental stage efficiency	Predicted stage efficiency (ref. 5)
	J/g	Btu/lb	J/g	Btu/lb		
1	25.31	10.88	26.61	11.44	0.836	0.856
2	26.17	11.25	27.00	11.61	.809	.823
3	25.79	11.09	25.61	11.01	.839	.836
4	27.17	11.68	25.21	10.84	.829	.850

TABLE I. - COMPARISON OF STAGE GROUP PERFORMANCE

WITH PREDICTED PERFORMANCE

Stage group	Equivalent specific work output		Experimental efficiency	Predicted efficiency (ref. 5)	Pratt & Whitney estimated efficiency (ref. 4)
	J/g	Btu/lb			
Stage 1	26.61	11.44	0.835	0.856	-----
Stages 1 and 2	53.61	23.05	.825	.846	-----
Stages 1 to 3	79.22	34.06	.844	.854	-----
Stages 1 to 4	104.44	44.9	.856	.867	0.893
Stages 1 to 4 and outlet turning vanes	104.44	44.9	.855	.862	.886

Comparison of Individual Stage Performance

The performances of the individual stages are compared in table II for the condition at which design 4½-stage specific work output was obtained. The stage performances were derived from the stage group tests by using the mass flow-specific work relation for stage 1 and for stages 1 and 2. For the group consisting of stages 1 to 3, the pressure ratio $P_0'/P_{2.5}$ was used to determine the three-stage group performance at the condition at which design 4½-stage work output was obtained. The first and second stages produced 0.95 and 0.97 of their design work outputs, respectively. The third stage produced very close to its design work output, and the last stage produced 1.08 of its design work output. The efficiencies of the first and fourth stages were about 0.02 lower than predicted, and that of the second stage was 0.014 lower. The third-stage efficiency was about equal to the predicted efficiency. Thus table II shows that all stages operated reasonably close to their expected performance levels and that the overall (4½ stage) performance was not degraded by any particularly inefficient component.

Summary of Results

A cold-air investigation was made at design equivalent speed to determine the performance of stage groups of a 4½-stage turbine that had a stage-loading factor of 4.66 and high specific work output. The pertinent results are summarized as follows.

1. The 4-stage turbine configuration produced design equivalent work output with an efficiency of 0.856, a barely discernible difference from the 0.855 obtained for the complete 4½-stage turbine at these conditions in a previous investigation. The effect of the outlet-turning-vane pressure loss on efficiency was estimated for this turbine as 0.005. The manufacturer's efficiency estimate for the 4½-stage turbine was 0.886, and the efficiency predicted by Lewis using a reference method was 0.862.

2. For the 4½-stage turbine the outlet turning vanes held the turbine exit flow angle to 6° or less; for the 4-stage turbine this angle varied from about 30° to 50° over the range of pressure ratio.

3. The efficiencies of the stage groups at their respective design work outputs varied from 0.007 low for the 4½-stage turbine to 0.021 low for the single-stage configuration—as compared with the efficiency predicted by a reference method.

4. The efficiencies of the individual stages were compared with predicted efficiency at the condition at which design 4-stage work output was obtained. The efficiencies of stages 1 and 4 were 0.02 lower than the predicted value, that of stage 2 was 0.014 lower, and that of stage 3 was about equal to the predicted value. Thus all stages operated reasonably close to their expected performance levels, and the overall (4½-stage) performance was not degraded by any particularly inefficient component.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio; January 25, 1980,
505-04.

References

1. Walker, N.D.; and Thomas, M.W.: Experimental Investigation of a 4½-Stage Turbine with Very High Stage Loading Factor. II – Turbine Performance. NASA CR-2363, 1974.
2. Whitney, Warren J.; Schum, Harold J.; and Behning, Frank P.: Cold-Air Investigation of a 3½-Stage Fan-Drive Turbine with a Stage Loading Factor of 4 Designed for an Integral Lift Engine. II – Performance of 2-Stage, 3-Stage, and 3½-Stage Configurations. NASA TM X-3482, 1977.
3. Wolfmeyer, G.W.; and Thomas, M.W.: Highly Loaded Multi-Stage Fan Drive Turbine – Performance of Initial Seven Configurations. NASA CR-2362, 1974.
4. Webster, P.F.: Design of a 4½-Stage Turbine with a Stage Loading Factor of 4.66 and High Specific Work Output. NASA CR-2659, 1976.
5. Stewart, Warner L.; and Glassman, Arthur J.: Analysis of Fan-Turbine Efficiency Characteristics in Terms of Size and Stage Number. NASA TM X-1581, 1968.
6. Bullock, R.O.; and Johnsen, I.A., eds.: Aerodynamic Design of Axial Flow Compressors. NASA SP-36, Revised, 1965.
7. Whitney, Warren J.; et al.: Cold-Air Investigation of 4½-Stage Turbine with Stage Loading Factor of 4.66 and High Specific Work Output. I – Overall Performance. NASA TM X-3498, 1977.

1. Report No. NASA TP-1688	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle COLD-AIR INVESTIGATION OF A $4\frac{1}{2}$-STAGE TURBINE WITH STAGE-LOADING FACTOR OF 4.66 AND HIGH SPECIFIC WORK OUTPUT II - STAGE GROUP PERFORMANCE		5. Report Date June 1980 6. Performing Organization Code
7. Author(s) Warren J. Whitney, Frank P. Behning, Thomas P. Moffitt, and Glen M. Hotz		8. Performing Organization Report No. E-315
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		10. Work Unit No. 505-04 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Paper 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The stage group performance of a $4\frac{1}{2}$-stage turbine with an average stage-loading factor of 4.66 and high specific work output was determined in cold air at design equivalent speed. The 4-stage turbine configuration produced design equivalent work output with an efficiency of 0.856; a barely discernible difference from the 0.855 obtained for the complete $4\frac{1}{2}$-stage turbine in a previous investigation. The turbine was designed by the contractor, and the procedure embodied the design features (1) controlled vortex flow, (2) tailored radial work distribution, and (3) control of the location of the boundary-layer transition point on the airfoil suction surface. The contractor's efficiency forecast for the $4\frac{1}{2}$-stage turbine was 0.886, and the value predicted by Lewis using a reference method was 0.862. The stage group performance results were used to determine the individual stage efficiencies for the condition at which design $4\frac{1}{2}$-stage work output was obtained. The efficiencies of stages 1 and 4 were about 0.020 lower than the predicted value, that of stage 2 was 0.014 lower, and that of stage 3 was about equal to the predicted value. Thus all the stages operated reasonably close to their expected performance levels, and the overall $\left(4\frac{1}{2}\text{-stage}\right)$ performance was not degraded by any particularly inefficient component.

17. Key Words (Suggested by Author(s)) Turbine aerodynamics High-stage loading	18. Distribution Statement Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	15	A02

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1980